Sensitivities and Speeds for Future Space- and Ground-based Imaging Surveys

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… and thanks to Alex Kim, SNAP, & LSST collaborations

More details in:
G. Bernstein, "Advanced Exposure Time Calculations", *PASP* January 2002

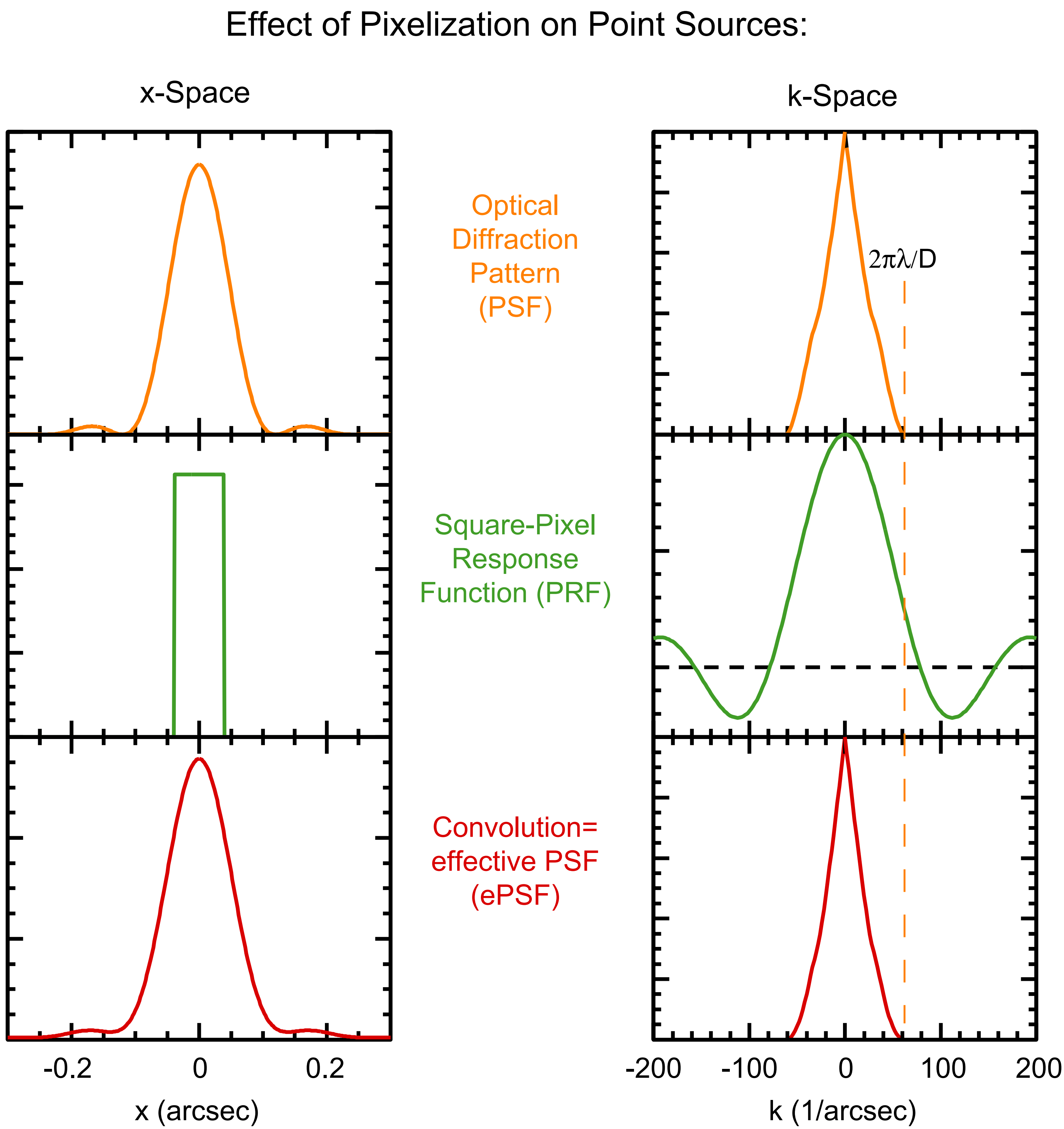
What is the most accurate possible information we can extract from astronomical images about

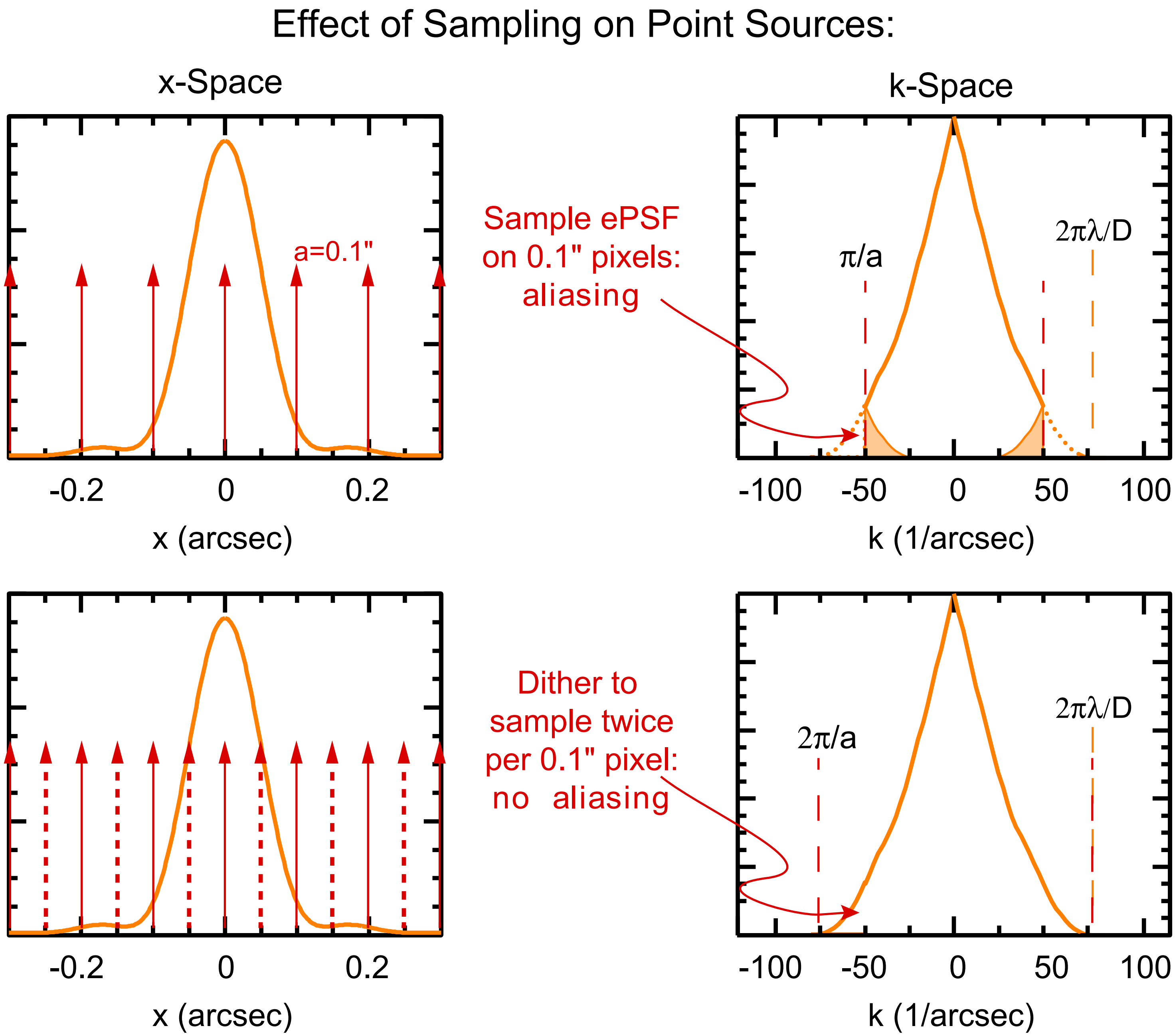
- Point source photometry (e.g. high-z supernovae)
- Point source astrometry
- Galaxy photometry
- Galaxy ellipticities (weak gravitational lensing)

When we take into account the effects of:

- Shot noise from source
- Shot noise from zodiacal and atmospheric sky brightness
- Detector read noise and dark current
- Finite resolution from diffraction, aberrations, and seeing
- Finite pixel size and sampling
- Dithering strategies
- Information loss from cosmic rays

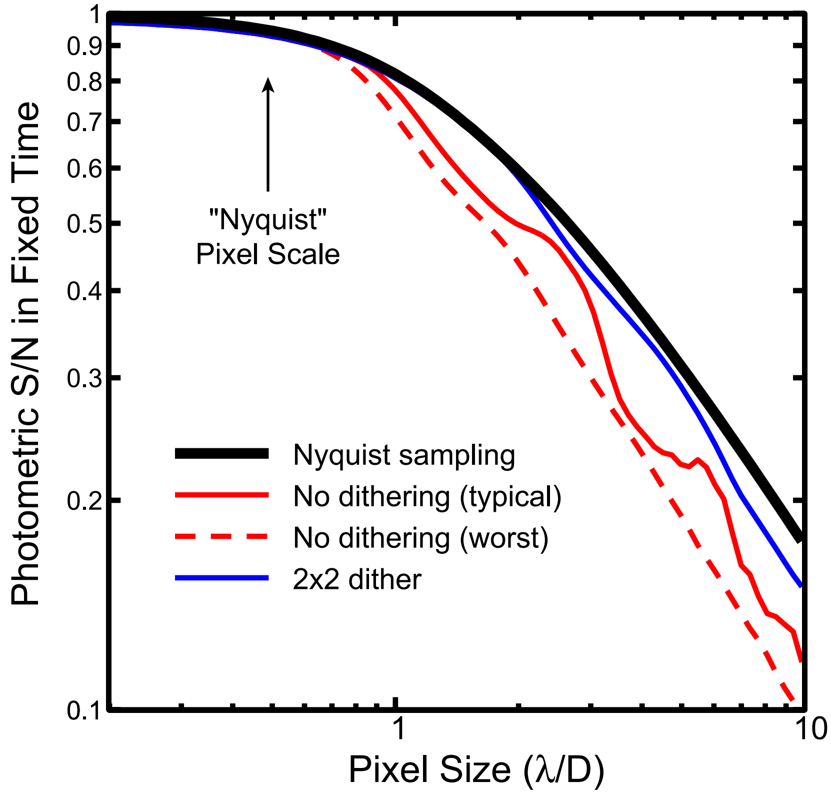
What do these calculations tell us about the design choices (e.g. ground vs space) for imaging surveys?

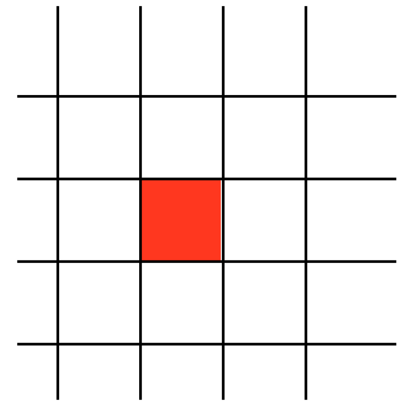

Effect of Pixelization on Point Sources:
x-Space
k-Space
Optical
Diffraction
Pattern
(PSF)
Square-Pixel
Response
Function (PRF)
Convolution=
effective PSF
(ePSF)
2πλ/D
-0.2
0
0.2
x (arcsec)
-200
-100
0
100
200
k (1/arcsec)



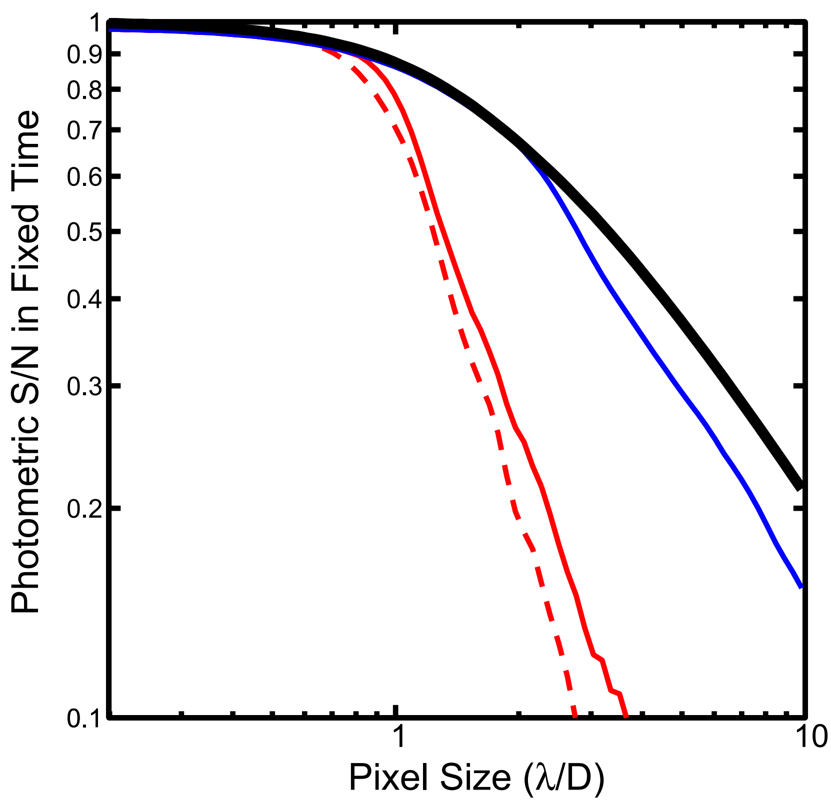
Effect of Sampling on Point Sources:
x-Space
k-Space
a=0.1"
Sample ePSF
on 0.1" pixels:
aliasing
π/a
2πλ/D
-0.2
0
0.2
x (arcsec)
-100
-50
0
50
100
k (1/arcsec)
Dither to
sample twice
per 0.1" pixel:
no aliasing
2π/a
2πλ/D
-0.2
0
0.2
x (arcsec)
-100
-50
0
50
100
k (1/arcsec)

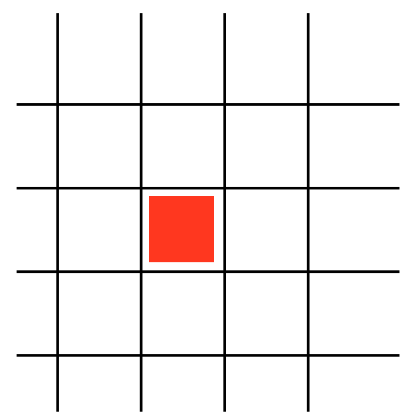
How Much Dithering is Best?
(for point-source photometry)





Perfect square pixel response





Pixel with 10% "dead zone"
at edges

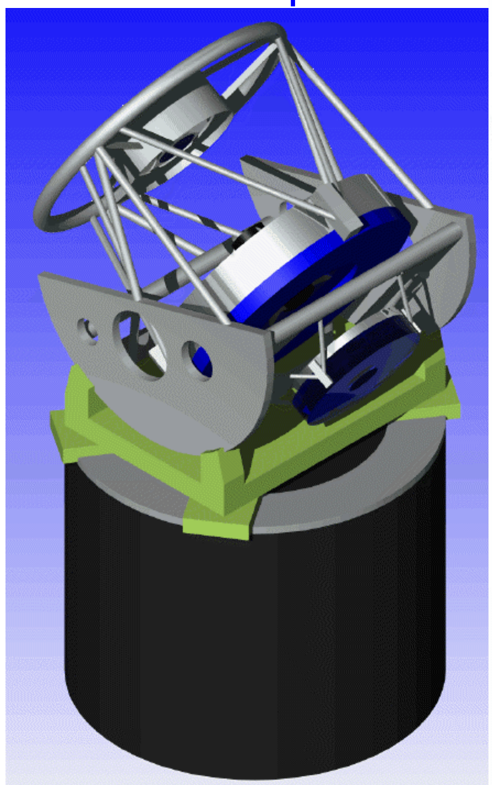
...2x2 dithering pattern recovers nearly all photometric information!

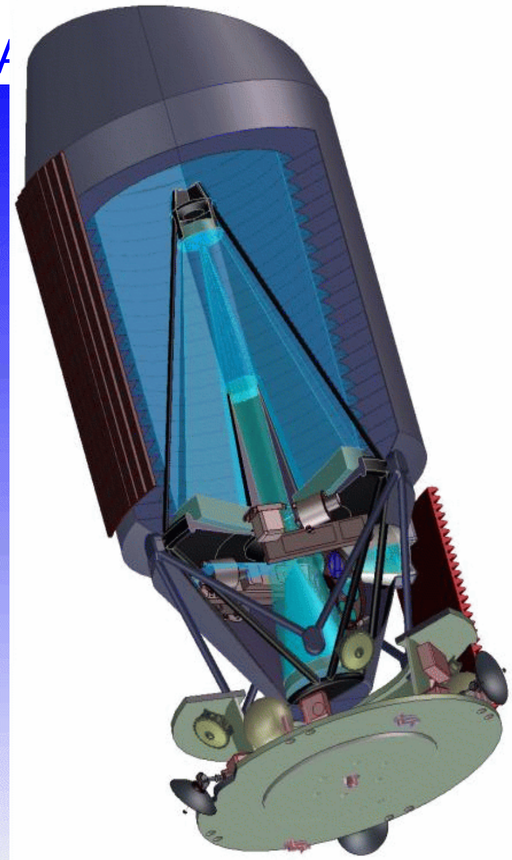
Billion-Pixel Observatories:

Large Synoptic Survey Telescope (LSST)

and

Supernova A … AP)

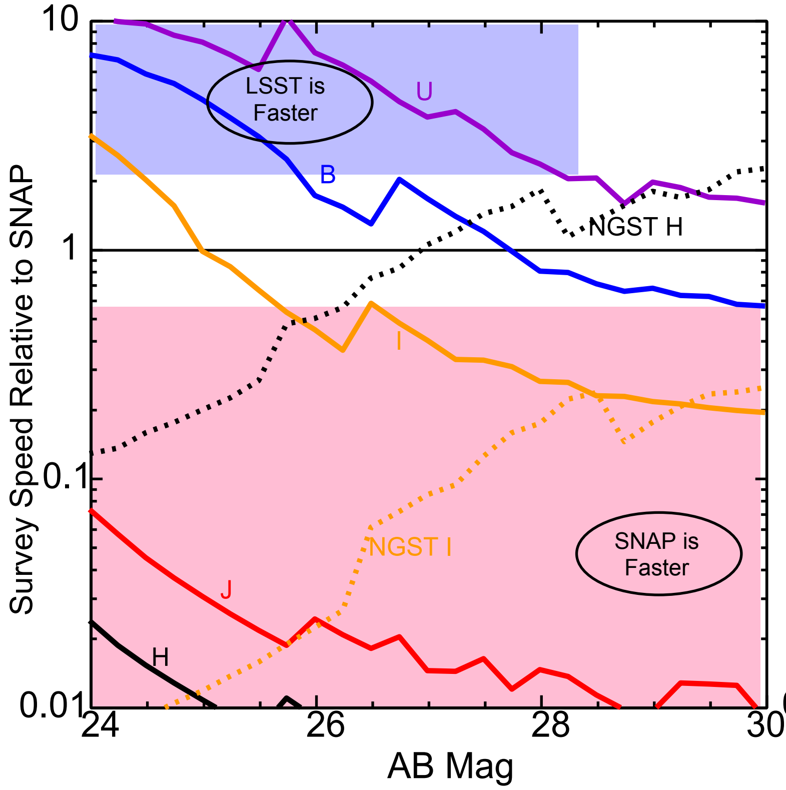




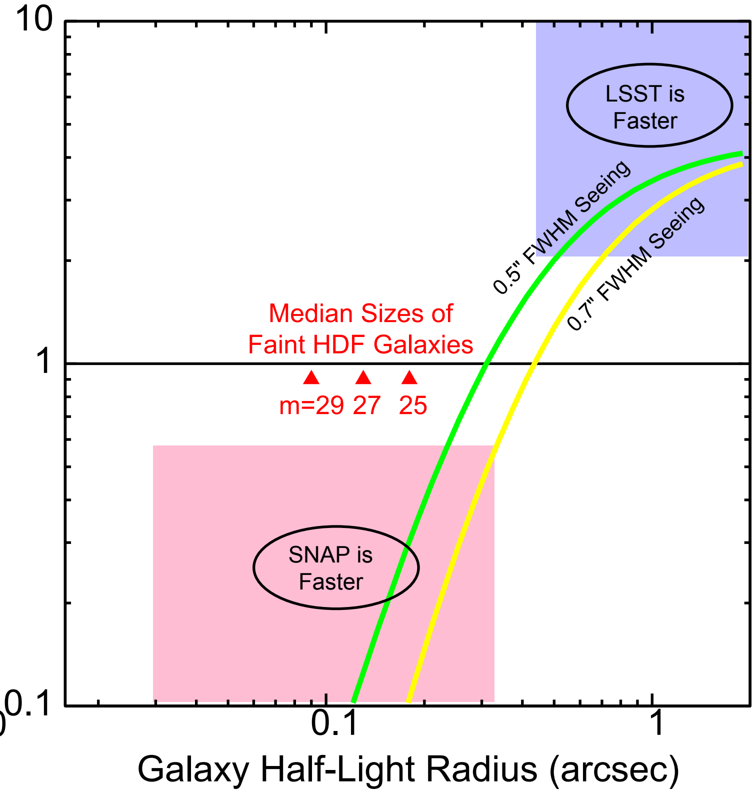
	LSST	SNAP
Primary Mirror Diameter	8 meters (6.5-meter equivalent)	2.0 meters
CCD Field of View	8 square degrees	1 square degree
Number of CCD pixels	$1.3x10^9$	$1.3x10^9$
Angular Resolution	0.5”-0.7” (atmospheric seeing)	0.05”-0.1” (diffraction-limited)
Platform	Ground	Space
Nominal Exposure	20 sec.	300 sec.

Which is more effective: ground or space survery?

for point-source photometry:



for galaxy shape measurements:



Noise sources favor ground-based for:

- Photometry of uncrowded points sources in U or B bands, or bright sources, e.g. SNe at z<0.7
- Weak lensing observations of large/nearby/bright (m<25) galaxies
- Detection of fast-moving sources, i.e. near-Earth objects

and space-based for:

- Photometry in I band or near-IR bands, e.g. SNe at z>0.8
- Weak-lensing measurements of m>25 objects for highest S/N and studies of dark matter evolution

Systematic errors favor ground-based for:

- Fast slews and rapid all-hemisphere coverage, e.g. NEOs and prompt gamma-ray burst followup

and space-based for:

- Stability of PSF and transmission give lowest systematic errors for point-source photometry and weak lensing.
- Stability gives near-perfect difference imaging, e.g. for SNe and microlensing.
- Stability of PSF and resolution best for crowded-field photometry of static sources
- High-earth orbits offer most reliable cadences for time-variable targets.

Fisher Information for point-source photometry:

For PSF-fitting of flux & position parameters to an image, the errors in fitted parameters are described by the Fisher matrix:

$$\mathbf{F}_{ij} = \sum_{k\in \text{pixels}} \frac{\dfrac{\partial I_k}{\partial p_i}\dfrac{\partial I_k}{\partial p_j}}{\mathrm{Var}\left(I_k\right)} \qquad \mathrm{Cov}\left(p_i, p_j\right) = \left(\mathbf{F}^{-1}\right)_{ij}$$

Sum over all pixels in all (dithered) exposures. In the event of a cosmic ray, we just skip the sum term for the affected pixels.

Figures of Merit for Nyquist-sampled, background-limited observations:

Photometry or detection of point sources:

$$\boxed{A_{S/N} = \iint d^2k \left|P^2(k)\right|\left|R^2(k)\right|}$$

Where *P(k)* and *R(k)* are the FT's of the optical PSF and the pixel response function.

Astrometry of point sources:

$$\boxed{A^2{}_{centroid} = \iint d^2k\, k^2 \left|P^2(k)\right|\left|R^2(k)\right|}$$

Measurement of galaxy ellipticities – *g(k)* is FT of galaxy profile:

$$\boxed{\sigma_e^{-2} \propto \iint d^2k\, k^2 \left|P^2(k)\right|\left|R^2(k)\right|\left|\left(\frac{\partial g}{\partial |k|}\right)^2\right|}$$